Collision Risk Circumstances and Traffic Routeing in the Approaches to the Strait of Juan de Fuca

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I. INTRODUCTION. This paper is concerned with collision risk reduction through the identification, measurement and analysis of contributing factors and the evaluation of risk control measures appropriate to the approaches to the Strait of Juan de Fuca. Risk factors were identified through a traffic survey and collision probabilities were estimated and modified by a simulated modification to traffic routeing. Marine collision risk analyses have tended to describe the circumstances of collisions without comparison to the conditions encountered by marine traffic. In the absence of any test of significance, such an analysis is revealing yet provides an incomplete basis for traffic management decisions. This study examines the importance of contributing factors through such a comparison.

The study area encompasses 1851 square miles, including the waters from 124° 40' W extending 54 miles to seaward to 126° W. It is bounded to the north by Cape Beale and the shoreline of Pacific Rim National Park and extends southward to 48° 12' N (Fig. I). Olympic National Park and Flattery Rocks National Wildlife Refuge are located along the Washington coast to the southeast. The international, Canadian and United States waters within this area are under continuous, recorded radar coverage from Tofino Vessel Traffic Services (VTS) at Ucluelet, British Columbia.

Shipping activity within the Canadian and United States ports of the Strait of Georgia and Puget Sound on the west coast of North America supported as many as 19887 vessel transits through the entrance of Juan de Fuca Strait during 1989. Freedom of movement in the approaches is further complicated by the presence of military exercise area W601 and the concentration of fishing vessels which frequent La Perouse, Finger, Soquel and Swiftsure banks. The collision of the factory fishing vessel *Tenyo Maru* and the freighter *Tuo Hai* in the approaches to the Strait of Juan de Fuca in July of 1991 illustrated the commonality in collisions occurring in the approaches to the Strait. The sinking and oil spill grasped public attention by illustrating several of many possible catastrophic consequences of collisions at sea - the loss of life, property and the fouling of the coastal environment.

Recent public concern for oil pollution has resulted in numerous government

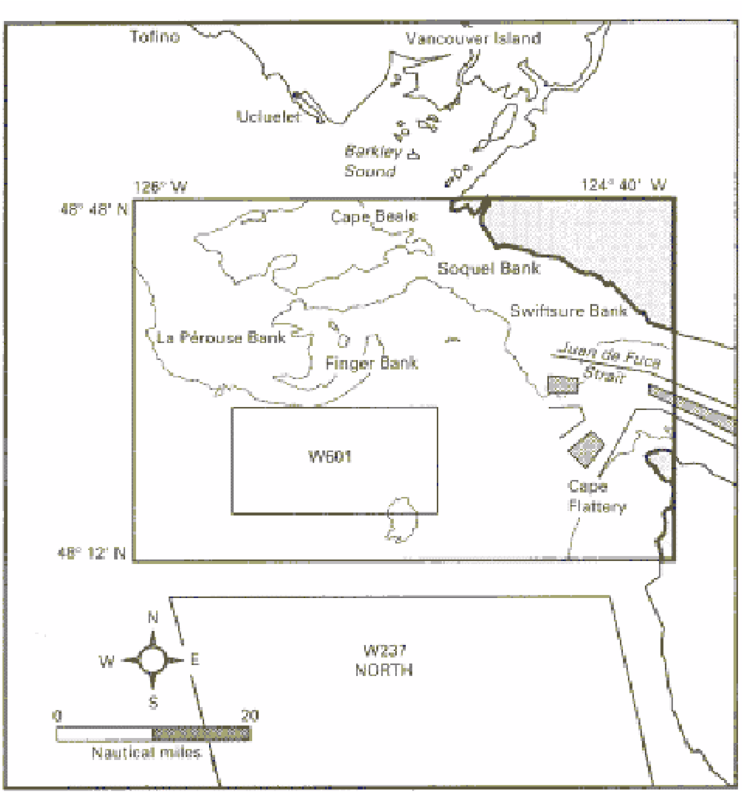

Fig. I. Approaches to the Strait of Juan de Fuca

investigations into tanker safety and spill prevention. In particular, Brander-Smith recommended that: 'As a priority, the Canadian Coast Guard examine existing traffic routeing schemes with a view to reducing the risk of collision due to traffic concentration at the entrance to Juan de Fuca Strait.'[1] Similarly, Anderson recommended that 'consideration be given to extending the routeing system some more miles to seaward of the entrance to the Strait of Juan de Fuca, so as to increase separation and to move the Far Eastern traffic route more to the west'[2]. These, and other reports are generally in harmony in recommending the, need to investigate the requirements for mandatory traffic routeing systems, tanker exclusion zones and vessel movement restrictions, according to weather and visibility limitations.

2. METHODOLOGY. Collision reports and casualty statistics for the period 1980-9 and the circumstances of a 1 percent sample of vessel transits during 1989 were analysed. Contributing factors examined included vcssel speed, visibility, traffic density and windspeed, as well as the seasonal and diurnal

variation in those factors found to be significant. The measurement of vessel speed and traffic density involved calculations based on historical transit records obtained from the Canadian Coast Guard and from government surveys of fishing vessel concentrations available at Fisheries and Oceans Canada. Climatological data for the study area were examined to determine the predominant visibility and windspeed encountered by each vessel in transit.

Vessel positions and times were plotted in a Geographic Information System. This system enabled both the determination of courses and speeds made good and the examination of traffic patterns and potential conflict areas. A database of possible contributing factors was created for statistical analysis.

Rather than simply using traffic volumes to represent the encounter rate experienced by each vessel in transit, average traffic density was estimated for each transit and collision by the use of a grid cell system. This enabled the inclusion of known fishing vessel concentrations in the traffic density estimates. The study area was divided into grid cells approximately 4- miles square in size, and traffic frequency and fishing vessel counts were determined for each cell. Each grid cell traffic density estimate summed the fishing vessel count, which was assumed to remain constant during a particular sample month, with the annual vessel traffic count, which was weighted by the average transit time through a grid cell, the ratio of monthly to total sample size (which reflects the monthly variation in traffic volumes) and the ratio of yearly traffic to the total sample size. It was calculated using the following formula where G is the estimated number of vessels per 19 minutes in cell ij during a particular month

$$G_{ij} = F_{ij} + V_{ij}\left[\frac{(d/S)}{H}\left(\frac{n}{N}\right)\left(\frac{T}{N}\right)\right]$$

and F is the fishing vessel count for grid cell ij in a sample month. V is the total sample transiting vessel count for grid cell ij in a sample year, d is the mean distance through a grid cell in miles, S is the sample mean transiting vessel speed in knots, H is the mean number of hours per month, n is the number of transiting vessels sampled in each month in 1989, *N* is the number of transiting vessels in a 1 percent sample of those vessels transiting the study area in 1989, and T is the actual number of transits in 1989 or the year of a collision.

Vessel traffic density data were derived by calculating the average density encountered by each vessel as it transited through each grid cell in the study area. The grid cell containing Buoy J was not included in calculating vessel traffic densities because most vessels passed through that area. Traffic density of collision incidents was approximated by using an average of the traffic densities encountered by each vessel prior to collision.

In order to determine if collision probability could be predicted by a Poisson probability function, the study area collision rate was expressed as a ratio of collisions per 5000 vessel transits through the approaches to the Strait rather than per some unit of time. This method accounted for the variation in traffic volumes throughout the year.

3. COLLISION REPORTS. Coast Guard records revealed a human error contribution to all collisions in the study area. A re-occurring theme of collisions involving excessive speed for the conditions of low visibility, high traffic density

TABLE 1. SELECTED SAFE SPEED FACTORS

Category	Definition
High visibility	Greater than 2 miles
Low visibility	Less than/equal to 2 Miles
High density	Greater than/equal to one vessel per 16 square miles
Low density	Less than one vessel per 16 square miles
High windspeed	Greater than/equal to 8 knots
Low wind	Less than 8 knots
Night	2000 to o8oo hours, or first (2000-2400), middle (0000-0400) and morning (o4oo-o8oo) watches
Day	0800 to 2ooo hours, or forenoon (0800-1200), afternoon (12oo-16oo) and dog (1600-2000) watches

or both was plain. The study area is characterized by conflicts among fishing vessels, through traffic and naval ships on exercise - 8 out of 10 collisions involved fishing vessels. Several reports indicated that VTS regulators either had difficulty discerning the developing close-quarters situations where numerous radar contacts overloaded their ability to track vessels, or they hesitated in providing advice necessary to arrest the escalating risk of collision.

4. TRAFFIC COMPOSITION AND GROWTH. Traffic was classified as freighters, tankers, tugs, government vessels and miscellaneous vessels. A comparison of the coefficient of variation in traffic volume for each category of vessels over the ten-year period indicated very little dispersion other than that resulting from growth. On average, freighters, which includes cargo and container vessels, comprised *61.1* percent of vessel traffic. This is followed by tugs and tows at *15.6* percent, tankers at 9.7, miscellaneous vessels at 7.8 and government vessels at 5.8 percent. Fishing vessels proceeding through the approaches accounted for 3.8 percent of traffic in 1989; however, the counts of vessels engaged in fishing grew by 3 percent from 311448 vessels in 1988 to 32510 vessels in 1989.

Traffic volumes grew steadily at three percent annually from *15 8* 2 *8* vessels in 19 *8* 0 to 19 *8 8* 7 in 19 *8* 9. Monthly traffic volumes for 19 *8* 9 varied from a low of 1269 vessels in February to a peak Of 2444 in July. For this reason, any analysis of collision probabilities for a given area should not necessarily use a collision rate per year as the sole bench mark for comparison.

S. EXCESSIVE SPEED FOR THE CONDITIONS. Factors which are considered when assessing safe speed were selected for an analysis of variance o average vessel speed in order to determine if vessel speeds were lower in restrictive navigating conditions. These factors included visibility, traffic density, windspeed and time of day. Also, collisions were compared with through traffic in terms of each factor. Table I lists the categories of factors for which mean speeds were calculated. The results are illustrated in Fig. 2.

'Low visibility' was defined as less than or equal to 2 miles in order to increase the likelihood that a difference in speed would become apparent. It was assumed that low visibility would require radar navigation which may not reveal all traffic; high traffic density would necessitate a higher level of attention and

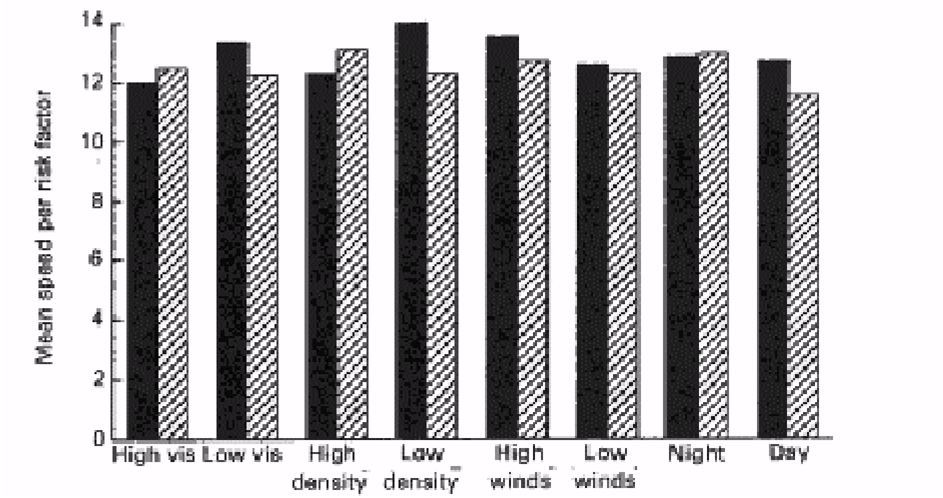

Fig. 2. Mean vessel speed by risk factors. ■, collisions; ▨, traffic

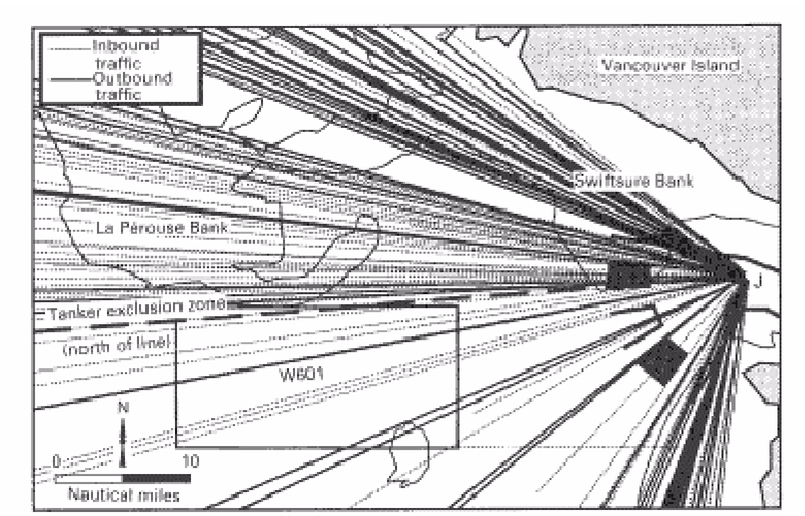

Fig. 3. Traffic flow in the approaches (Judson, 1992)

anticipation of manoeuvring; windspeeds of over 8 knots may degrade radar performance because of sea clutter on the display concealing small contacts, as well as hindering manoeuvrability; and navigation at night may be hampered by back scattering of light interfering with vision, as well as the possibility of confusion when identifying navigation lights or vessel movements.

Figure 2 shows that, on average, mariners proceeded through the study area at 12.5 knots without any prudent reduction in vessel speed. Of the sixteen conditions compared, no two groups' average vessel speeds varied significantly at

TABLE 2. MEAN INBOUND AND OUTBOUND TRAFFIC ROUTES

	Mean course	Standard deviation	Minimum Course	Maximum course	Frequency
Inbound routes	101°	14.24°	070°	125°	66
	022°	14'.92°	010°	o6o°	38
	143°	25.00°	130°	180°	4
Outbound routes	292°	16.66°	250°	305°	40
	201°	8.48°	189°	230°	38

the 0.05 level. Since vessel speed did not vary, excessive speed is a factor which is not solely associated with collisions. This finding supports conclusions reached elsewhere that mariners accept a level of risk beyond any reduced risk associated with on-board technological improvements in navigation equipment.

6. VISIBILITY AND WINDSPEED. Since the intention was to analyse the environmental conditions encountered by mariners, not describe the climate of the study area, the occurrence of climatological factors corresponds with the frequency of vessel transits. Greater than 90 percent of traffic proceeded through the study area with a visibility greater than 2 miles, whereas six out of ten collisions occurred in restricted visibility. As expected, an average traffic visibility of 11.2 miles was found to be significantly greater than an average collision visibility Of 4.6 miles (t value 4.42, D.F 193, 1-tail P = 0.001). Furthermore, average visibility was lowest during the morning watch when collision frequency was greatest. This finding confirmed the expectation of a lower visibility during this period due to fog formation in the early morning, and further supports the association of poor visibility and collisions.

The finding that most collisions occurred in restricted visibility suggested that an association with low average windspeeds would be found. Indeed, the mean windspeed during collisions was 4.7 knots compared with 7.2 knots experienced by vessels in transit. Since over 76 percent of vessel traffic experienced windspeeds of less than I I knots, it is suggested that windspeeds, seastate and degraded radar performance are not significant contributors to collisions within the study area.

7. SPATIAL PATTERN OF TRAFFIC AND COLLISIONS. A most striking traffic pattern resulted from the plotting of courses made good by vessels through the study area. This was the pronounced separation of inbound and outbound traffic in the west and northwest approaches to the Strait (Fig. 3). Since traffic routeing is limited to territorial waters, voluntary traffic separation in the international waters of the study area occurs in the absence of any traffic routeing scheme.

The Canadian Coast Guard requests that loaded inbound tankers refrain from operating within the Tanker Exclusion Zone (TEZ) and advises that 'vessels approaching these areas from any direction. . pass to seaward and clear of the banks' and that 'vessels which are obliged to cross the banks should navigate with extreme caution in order to avoid risk of collision with fishing vessels'.[3] The TEZ is voluntarily observed by inbound oil tankers from Valdez, Alaska, and is designed to keep tankers a sufficient distance offshore so that the risk of grounding is reduced should a propulsion or steering breakdown result in a foundering. While these two recommendations should result in additional caution, several other explanations are offered which may better explain this traffic pattern.

Figure *3* shows that ship routes are concentrated in three arcs converging on Buoy J. Mean inbound and outbound courses for these arcs are compiled in Table 2. In addition a mean course of *143* ° was determined for nearshore traffic proceeding inbound from Vancouver Island harbours.

It would appear that mariners select a nearly easterly approach route to the Strait with an average course of 101 ° to avoid head-on traffic which is outbound to the northwest (Table 2 and Fig. *3).* This route approximates the recommended main shipping route from Japan indicated in *Sailing Directions, British Columbia Coast.*[4] Outbound traffic proceeding to the Far East tends to diverge in an arc to the northwest. An average course Of 292° approximates the great circle route to Japan. Again, this route avoids encountering much of the inbound traffic.

Unfortunately, through traffic does not, on average, pass to seaward of the banks. Furthermore, it is obvious that inbound traffic tends to remain clear to the north of military exercise area *W601* (currently being eliminated) even though it has been active on a discontinuous basis only, Because the time of its activation by the military was communicated to mariners by VTS regulators, it is suggested that this area may have been perceived as a hazard because it was avoided by *93* percent of traffic in the approaches. The combined result is that traffic which might otherwise keep clear to the south of the banks is constrained to proceed through the most active areas of La Perouse and Swiftsure banks. Since the Canadian Hydrographic Service recommends that seiners and trawlers be given a berth of at least *914* m,[5] this would require continuous manoeuvring if one were to proceed through the fishing fleet.

Nearshore coastal traffic, inbound from Port Alberni and elsewhere, tends to proceed on an average course of *143* °. This traffic tends to remain clear to the north of traffic outbound to the Far East; however, it is particularly exposed to head-on encounters, as well as fishing activity in summer.

Traffic close to the Washington coast proceeds on a mean course Of 201° when southbound and its near reciprocal 022 ° when approaching the Strait. On average, there appears to be little separation of traffic compared to the Far East route. The absence of a head-on collision in this area during the study period may be testimony to the mariners' abilities to correctly apply steering and sailing rules, however, the potential consequences of error in this area necessitate further evaluation of traffic routeing.

The traffic routeing scheme recognized by the IMO, which extends 12 miles from shore, appears limited to an approach or departure point for overseas traffic. Contrary to recommendations by the Coast Guard, vessels tend to manoeuvre through fishing areas rather than avoiding them entirely.

8. TRAFFIC DENSITY. The spatial correspondence between the location of collisions and the fishing banks, as indicated by the 100m depth contour, is most visible in Fig. *4.* Traffic density was greatest on the fishing banks and reached a

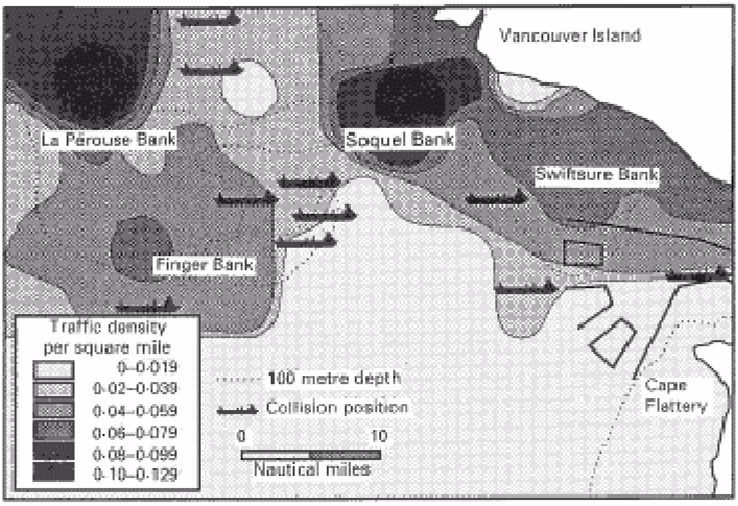

Fig. 4. Traffic density, fishing banks and collision positions (Judson, 1992)

maximum mean annual density of 0.125 vessels per square mile on Soquel Bank. lt is suggested that the proximity of collisions to the extremity of the fishing banks is the result of the mariner's attempt to avoid the heaviest concentration of fishing vessels and reduce distance overall by navigating too close to a group of fishing vessels. This association of traffic density and collisions is further supported by a comparison of mean traffic density encountered by through traffic and vessels in collision, as well as a seasonal comparison.

Vessels in transit encountered a mean traffic density of 0.67 per grid cell (4 x 4miles) or six vessels within a 6-mile range. By comparison, vessels involved in a collision encountered a significantly higher average traffic density of 2.16 per grid cell or 19 vessels within a 6-mile range (t value –4.24, D.F. 194, 1-tail P = 0.001). Theoretically, the collision rate increases with the square of the traffic density.[6] One would expect that the collision rate should be proportional to traffic volumes. The average number of collisions per month, derived over the ten-year study period, was compared with traffic volumes estimated for 1991 (Table 3). Monthly traffic volumes were estimated by proportioning the annual volume of 21141 vessels (estimated by an annual increase of 627 vessels since 1989) according to the 1989 monthly distribution. This comparison resulted in a correlation of r = 0.96 between the monthly collision rate and traffic volumes which implies a higher collision risk per ship during months with high traffic volumes (r = 0.96, r2 = 0.92, S.E. est. 0.03, sig. 0-0000).

Average traffic densities encountered by transiting vessels were used in this study to enable comparisons which were independent of route length, since route lengths through the study area varied. Nevertheless, the distance travelled by a vessel through the study area was considered in the design of an alternate routeing scheme. Changes in traffic routes could affect route lengths and traffic densities

TABLE 3. ENCOUNTERED DENSITY, SHIP-MILES AND COLLISION RATE, 1991

Month	Mean traffic density encountered	Number of transits	Ship-miles	Density x ship-miles	Observed collision frequency	Expected collision frequency
January	0.14	1442	49850	6869	0.0	0.01
February	0.11	1349	46645	4944	0.0	0.01
March	0.16	I577	54522	8669	0.0	0.02
April	0.19	1687	58345	11132	0.1	0.02
May	0.22	1769	61164	13615	0.1	0.02
June	0.65	1949	67381	43568	0.1	0.08
July	2.04	2598	89854	182870	0.3	0.32
August	1.50	2346	81127	121252	0.3	0.21
September	1.52	198S	68655	104067	0.1	0.18
October	0.13	1583	54754	6965	0.0	0.01
November	0.12	1436	49657	5790	0.0	0.01
December	0.13	1420	49116	6248	0.0	0.01

encountered. Therefore, rather than just explore the relationship between traffic density and collisions, a causal relationship was examined by the inclusion of traffic frequency through areas of varying density via routes identified in Fig. 3 and Table 2.

The parameters used in regressing collisions with encountered density are listed in Table 3. The collision rate was defined as the number of collisions per month averaged over a 10-year period, and traffic density was defined as the product of average traffic density encountered per month and total ship-miles per month. A three percent growth in traffic and fishing activity is assumed which is based on findings indicated previously. Accordingly, traffic densities and transit volumes for 19 8 9 were increased by three percent. This 'best estimate' does not affect the correlation.

The method of determining ship-miles per month is the equivalent of the sum of total distance travelled by all vessels transiting in a month. The traffic pattern depicted in Fig. 3 appears to exhibit an equal dispersion of courses within each distinct arc. Therefore, the route lengths of mean courses were used in the calculation of monthly ship-miles. Since it is assumed that the monthly traffic pattern other than volume does not vary between months, total ship-miles per month is equivalent to the product of the number of transits and the average route length Of 34.6 miles.

To ensure that a nonsensical collision rate would not be estimated for an

independent variable value of zero, a regression throuah the origin was performed on the collision rate with encountered traffic density times ship-miles such that,

$$\hat{y} = 0.000\,00\,1\,76X$$

where $\hat{y}$ is the estimated collision rate per unit of vessel traffic density times shipmiles and X is the estimated monthly traffic density (vessels encountered per grid cell) times ship-miles. This relationship indicates an r^2 value Of 0.87 where 87 percent of the total variation is explained by the regression (D. F. 11, S.E. est. 0.05, sig. 0.0005, S.E. slope 2.05 x 10^{-7}). Expected and observed numbers of collisions per month are included in Table 3. This finding is consistent with the nature of collisions in the study area which were shown to involve concentrations of fishing vessels and through traffic. During the peak traffic months of July and August, six out of ten collisions occurred. During an entire fishing season from June through September, 42.5percent of yearly traffic transited the approaches during which eight out of ten collisions occurred. This finding provided the basis to test the hypothesis that the rare event of a collision occurs as a Poisson distribution in relation to vessel traffic frequency and time.

9. COLLISION PROBABILITY. Since the collision rate is correlated to vessel traffic frequency, the mean number of collisions (A) is expressed as a ratio of the number of collision incidents to the total number of periods during which 5ooo vessels transited the study area. The collision rate per 5000 transits was used to estimate the mean or expected value,

$$\lambda = \frac{i}{n}$$

where n is the number of periods during which there were 5ooo vessel transits and i is the total number of collisions. Therefore,

$$l = \frac{10}{34} \Big/ 5000 = 0.29/5000$$

According to the Poisson distribution, the probability that there will be r collisions is

$$P_{(r)} = \frac{\lambda^r e^{-\lambda}}{r!}$$

where λ equals 0.29, e = 2.7183 ..., and r!, called factorial r, is equal to r (r- 1) (r- 2) ... 1. A Kolmogorov-Smirnov goodness of fit test comparison of observed collision frequencies with estimated Poisson probabilities demonstrated a good approximation to a Poisson distribution (sig. 0.005). Therefore, the probability of at least one collision is 1-P(O) or 0.25 per 5ooo transits.

Accepting that collision frequency can be approximated by a Poisson distribution and predicted from encountered traffic density, a risk model was developed from which risk reduction can be estimated. This relationship provided a method of predicting the collision rate based upon traffic density which is a factor which can be modified by traffic routeing measures. This was accomplished by using the regression function of collision rate on traffic density x ship-miles as an estimate of λ in the Poisson model. Estimated collision rates for each month were then substituted for λ in the Poisson function such that,

$$P_{(r)} = \frac{1}{r!}\left[0{\cdot}000\,001\,76 X^r e^{-0{\cdot}000\,001\,76 X}\right]$$

and the probability of at least one collision was calculated for each month of 1991 (Fig. 5). This figure illustrates monthly collision probabilities of at least one

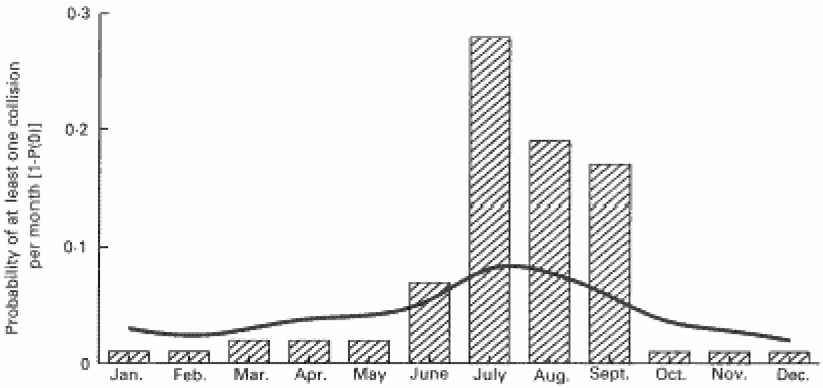

Fig. 5. Monthly collision probability, 1991. ▨, *Status quo*; —— modified scheme

collision $(1\text{-}P_{(O)})$ as a Poisson function derived from the regression estimate of lambda. Collision probability for the ***status quo*** is estimated to peak in July with a 28 percent chance of at least one collision occurring; the probabilities determined for a modified routeing scheme will be discussed.

10. VTS, SPEED CONTROL AND TRAFFIC ROUTEING. Within the control area of Tofino VTS, speeds are limited in a passive sense by Rule 6.[7] The Canadian VTS is burdened by the difficulty of not appearing to restrict or direct traffic when trying to improve safety; however, in practice, Tofino VTS regulators frequently offer and respond to requests for courses to avoid dense fishing activity.[8] Speed recommendations are only implied in the nature of information given to mariners regarding weather and vessel activity. Because speed is recognized by the United States Coast Guard as a particular problem in the Strait, speed limits are one of several navigation safety initiatives being considered. However, speed criteria are only being considered for tankships and chemical carriers under escort by tug, such that the speed does not exceed the operational speed of the escort.[9] This initiative is limited in its scope because it does not consider all vessels, nor the approaches to the Strait. Furthermore, a single speed limit could not be low enough to be considered appropriate in all circumstances. Criteria for the determination of excessive speed could be investigated by the Canadian and United States Coast Guards. Policing activity is limited to the registering of formal complaints or infractions which are then investigated. The recognition and interception of rogue vessels by VTS regulators and a support craft such as a fast patrol boat or hovercraft would enhance VTS effectiveness.

Several key user groups, including the Company of Master Mariners, the Department of National Defence and fishing organizations, have expressed concern about traffic routeing conflicts in the approaches to the Strait. In the past, the Canadian fishing community has opposed any restrictions on its activity resulting from the implementation of mandatory routeing schemes. This opposition resulted in a Canadian modification to Rule 10 which exempts a vessel fishing in Canadian waters or fishing zones from complying with Rule 10 sections (b), (c) and (h). The effect of these exemptions is that fishing vessels may continue their normal activity, which often involves unpredictable manoeuvring, as long as the passage of vessels following the traffic lane is not impeded. However, the British Columbia Deep Sea Trawlers Association and other fishermen have expressed both a concern about traffic congestion and the need to change routeing in the approaches.[10]

The Canadian Department of National Defence has an interest in the United States maintaining *W601*I as a surface and air gunnery exercise area, but a recent decision by the United States military has promulgated its removal. However, the location of W601 for the purpose of anti-submarine warfare exercises seems irrelevant, considering that the Canadian Navy regularly operates outside of this area. Therefore, it seems likely that the shifting of W601 to a less central area, or its elimination and substitution by the use of W237N to the south, would reduce traffic conflict, but it would not eliminate the possibility of a collision with a naval vessel not operating radar, such as occurred with HMCS *Kootenay* in *1989.*

1 1. ALTERNATIVE TRAFFIC ROUTEING. Various means of reducing traffic density in the approaches were considered. An 'Area to be Avoided' could be examined for the area of the fishing banks in order to protect United States and Canadian national parks. A separation scheme extending to the south along the Washington shoreline could reduce the risk of collision in that area, but would require further study of local fishing activity. The most promising risk control measure for the study area is the routeing of traffic 40 miles southwest of Buoy J, between the Canadian and United States fishing zones. A traffic separation scheme of 4 miles width, such as that illustrated in Fig. *6,* would meet IMO's

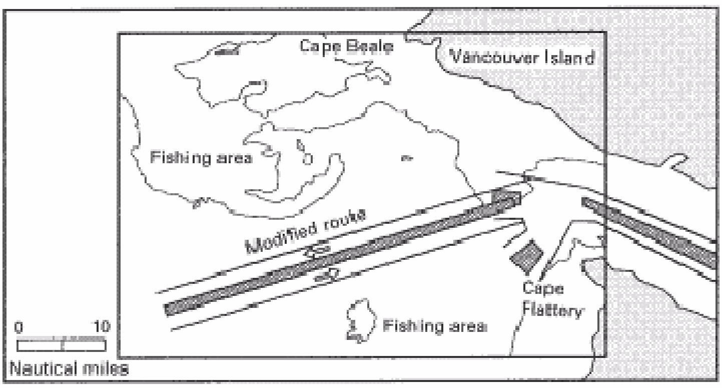

Fig. 6. Proposed alternate routeing scheme (Judson, 1992)

design criteria and reduce traffic density resulting in a lower collision probability.

Figure 5 illustrates the collision probability for the status quo and a modified scheme. If it is assumed that the fishing vessels count within the proposed lanes would be zero and that all Far East traffic is re-routed clear of the fishing banks, this scheme would result in a 68 percent reduction of the collision probability in the peak month of July to 0.09, and an annual reduction of 40 percent.

12. CONCLUSIONS. The problem of marine collisions in the approaches to the Strait of Juan de Fuca was investigated with the purpose of identifying causal and contributory factors and reducing casualties that frequently result in property loss, toxic spills and loss of life.

An attempt was made to improve upon existing methodologies used to study marine traffic in Canada through the use of a survey of marine traffic patterns and the estimation of a geographic collision risk. Initially, the causal and contributory factors to marine collisions in the study area were identified to direct the investigation towards practical and applicable solutions to the specific problems encountered.

Microwave imagery, conventional radar and related data are available in a form which can be used to reconstruct traffic patterns. GIS was used to plot traffic positions obtained from VTS radar and calculate traffic density, courses and speeds. A depiction of traffic patterns was achieved by using GIS that could not be represented by volume data alone. Through vessel traffic nearly doubles in frequency during the summer months, the same period of intense fishing activity. While vessel traffic tends to separate into inbound and outbound sectors, average traffic routes pass through the most active fishing areas.

Traffic density and reduced visibility were the most significant factors contributing to ten collision incidents. Excessive speed was found to be prevalent during restrictive navigating conditions. This result precluded finding statistically higher speeds associated with collisions. However, 8 out of 10 collisions involved excessive speed, 7 occurred in areas of high traffic density and 6 occurred during restricted visibility. Because mariners proceeded through the approaches to the Strait uncontrolled at an average speed of 12.5 knots, and without a significant reduction in vessel speed where prudent, it can be assumed that an inappropriate level of risk was accepted. As a minimum, the extent of this problem demands intervention to increase awareness. However, in the absence of more active traffic controls, vessels will continue to exercise their right to free passage, with life, property and the environment at risk. It must be concluded that the passage of traffic through the fishing grounds is inappropriate.

A regression of collision rates with the product of encountered traffic density and ship-miles resulted in a useful correlation (r^2 value of 0.87). This relationship was anticipated, as the literature supports, in theory, an association between traffic density and collisions. The correlation of $r = 0.96$ with traffic volumes also supports this finding. A Poisson distribution was used to derive collision probabilities from collision rates predicted by the regression function. The Poisson model was shown to compare well with observed collision frequencies in the study area. The benefit of traffic routeing in the approaches to the Strait was demonstrated by a quantitative reduction in absolute risk. It was found that, by routeing traffic clear of the fishing banks, the probability of collision during the peak traffic month of July was reduced by 68 percent and the annual collision risk by 40 percent.

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KEY WORDS

1. Collision avoidance. 2. Traffic separation schemes. 3. Vessel traffic services. 4. Risk analysis.